

Specific whole-body shifts induced by frequency-modulated vibrations of human plantar soles

Anne Kavounoudias^{*}, Régine Roll, Jean-Pierre Roll

Laboratoire de Neurobiologie Humaine, UMR 6562, CNRS-Université de Provence, Marseille cedex 20, France

Received 28 January 1999; received in revised form 16 March 1999; accepted 19 March 1999

Abstract

This study sought to analyze the postural responses induced by separately or simultaneously vibrating with different frequencies the forefoot and rear foot zones of both soles in standing subjects. Stimulating each zone separately resulted in spatially oriented body tilts; their amplitude and velocity varied linearly according to the frequency, and their direction was always opposite to the plantar site vibrated. When the two zones were each co-stimulated at different frequencies, the parameters of the postural responses depended on the frequency difference. When this frequency difference was zero, no clearly oriented body tilts occurred. We concluded that the change in the relative pressures evoked by differently co-vibrating these zones gave rise to regulative postural adjustments able to cancel the simulated body deviation. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Posture; Plantar mechanoreceptors; Vibration; Center of pressure (COP)

A posture is characterized by specific multisensory inputs whose main feature is to vary according to every postural change. Conversely, modifying or suppressing one of these inputs impairs postural control, for instance by cooling [7] or anesthetizing [1,10] the plantar soles or by applying an ischemic block above the ankles [2,3,4]. Also, changing the characteristics of the supporting surface on which subjects are standing delays the ankle muscle responses induced by a sudden toes-up rotation of the platform [12].

These methods, however, stimulate or deprive the plantar soles as a whole, yet there are two main supporting areas in each sole: the heel zone and the anterior zone overlapping the five metatarsal heads. We had shown that a 100 Hz frequency vibration applied to the anterior or posterior foot zones of standing subjects caused spatially oriented whole-body tilts depending on the zone stimulated [5]. Because unitary responses of cutaneous mechanoreceptors increase linearly with the vibration frequency [8], the parameters of these body tilts would be modulated by patterned frequency vibrations. For this purpose, we first separately stimulated the forefoot and rear foot zones with various vibration frequencies (20, 60, 100 Hz). Second, we

attempted to create an artificial contrast between the pressures by simultaneously applying different vibration-frequency patterns (frequency range 0–100 Hz) to the forefoot and rear foot zones. If one considers that upright quiet stance is characterized by a specific distribution of the body weight between the various supporting foot areas, every whole-body movement would modify this distribution. For example, when the body is tilted forward, the plantar pressures under the forefoot zones of both soles increase while they inversely decrease under the rear foot ones. Therefore, during sagittal whole-body tilt, a spatially relevant cue indicating the body position could emerge from the relative pressures exerted on each of these ‘sensory antagonist’ cutaneous areas.

Nine healthy volunteers (four men, five women, 22–55 years) participated in the experiment with the approval of the local Ethics Committee.

To selectively stimulate their plantar mechanoreceptors, we used four electromagnetic vibrators fixed independently on the ground, under an elevated rest, so that each vibrator probe passed through a hole in this foot rest to flush with the soles. The probes of the heel vibrators were round (40 mm diameter). Those of the anterior vibrators (ellipse: 30 and 75 mm of the axis lengths) overlapped the five metatarsal heads of the soles. The vibrators were driven by rectangular pulses (5 ms) coupled to power amplifiers. Their amplitude (0.2–0.5 mm) was controlled by a photocell system mounted in

^{*} Corresponding author. Tel.: +33-491-288295; fax: +33-491-288669.

E-mail address: anneka@newsup.univ-mrs.fr
(A. Kavounoudias)

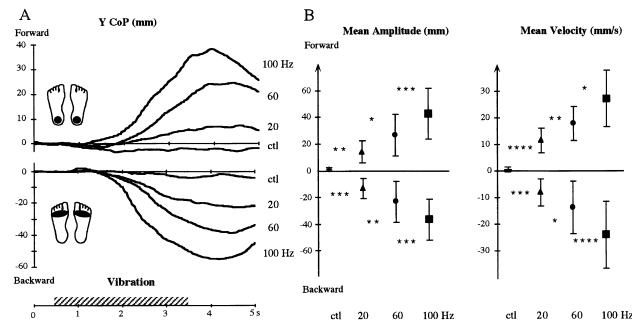


Fig. 1. Y-CoP displacements induced by separate stimulation of the forefoot and rear foot zones at 20, 60 and 100 Hz and control (ctl). (A) One subject's mean Y-CoP displacements. (B) Amplitude and velocity (mean ± SD) of all subjects' Y-CoP displacements (**P* < 0.05; ***P* < 0.01; ****P* < 0.005; *****P* < 0.0005).

the vibrator probes. A force platform including four transducers was set under the foot rest. Recordings (sampling rate: 50 Hz) of the antero-posterior (Y) and lateral (X) displacements of the CoP exerted by the feet started 500 ms before the onset of the vibration and lasted 5 s.

The participants stood barefoot on the foot rest with their eyes closed. They were first evaluated in a control condition (without vibration). Then, 12 experimental conditions with different vibration patterns were randomly tested. A first block of nine conditions consisted in co-stimulating with 20, 60 or 100 Hz either the two anterior, or the two posterior, or both zones of the soles. In the second block of three conditions, the vibration frequency and the zones activated varied during stimulation. Among these three conditions, two are referred to as 'static contrast': a 1 s stimulation with 100 Hz was first simultaneously applied to the forefoot and rear foot areas of both soles; then, either the anterior or the posterior vibrators were stopped so that only the two forefoot or rear foot areas were stimulated another 2.5 s. In the third of these conditions, 'dynamic contrast', the anterior and posterior areas of both soles were co-stimulated (1.5 s) as follows: the two anterior areas were stimulated following a sinusoidal pattern of vibration frequency increased by increments of 100 ms from 50 to 100 Hz, and then decreased from 100 to 50 Hz while the same sinusoidal pattern, but in opposing phase, was applied to the two posterior areas.

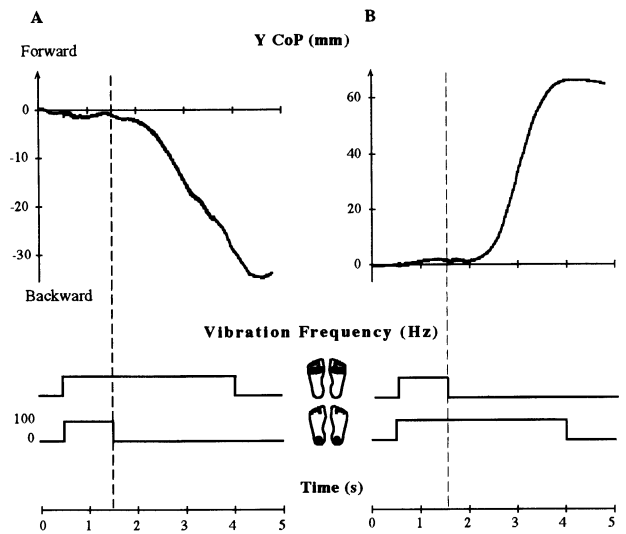


Fig. 2. Mean Y-CoP displacements of one subject under the 'static contrast' conditions where both foot zones were first co-stimulated (100 Hz, 1 s) and then only the forefoot (A) or rear foot (B) zones were stimulated longer (100 Hz, 2.5 s).

Vibration-induced body sways are frequency dependent: whatever the frequency used, applying superficial low amplitude vibration to the two posterior or anterior areas of both soles induced whole-body tilts. Their direction was roughly oriented in the sagittal plane and opposite to the vibrated plantar sites, i.e. forward and backward, respectively. For both stimulation conditions, the mean X-CoP positions after 2.5 s-vibration were negligible (5.5, 3.5 and 1.8 mm, at 100, 60 and 20 Hz). Fig. 1A shows the mean trajectories of one subject's Y-CoP displacements when we co-stimulated the two rear foot or forefoot regions at 20, 60, or 100 Hz. The highest and fastest postural responses occurred at 100 Hz and the smallest and slowest ones at 20 Hz, with intermediate values at 60 Hz.

Under all the experimental conditions, the mean latency of the postural sways, which were automatically determined at ±2 SD above the resting position, was on average 0.9 ± 0.4 s. The amplitude and the velocity of each response was calculated by fitting a linear regression of the Y-CoP sway from the onset of the sway up to 2.5 s of vibration. Separate one-way Anovas showed that the mean amplitude and velo-

Table 1

Influence of the vibration frequency on the amplitudes and velocities (mean ± SD) of X- and Y-CoP displacements of all subjects after co-stimulation of the forefoot and rear foot zones of both soles

Frequency (Hz)	X CoP		Y CoP	
	Amplitude (mm)	Velocity (mm/s)	Amplitude (mm)	Velocity (mm/s)
100	0.3 ± 1.42	0.09 ± 0.64	-2.13 ± 3.79	-1.66 ± 2.51
60	0.15 ± 0.47	-0.32 ± 1.21	-0.47 ± 1.65	-0.66 ± 1.52
20	0.19 ± 0.65	0.12 ± 0.37	0.33 ± 2.71	0.00 ± 0.59
Control	0.5 ± 0.88	0.1 ± 0.29	0.34 ± 1.78	-0.25 ± 0.36
	<i>F</i> (3,24) = 0.23 <i>P</i> > 0.5	<i>F</i> (3,24) = 0.67 <i>P</i> > 0.5	<i>F</i> (3,24) = 1.42 <i>P</i> > 0.5	<i>F</i> (3,24) = 2.11 <i>P</i> > 0.5

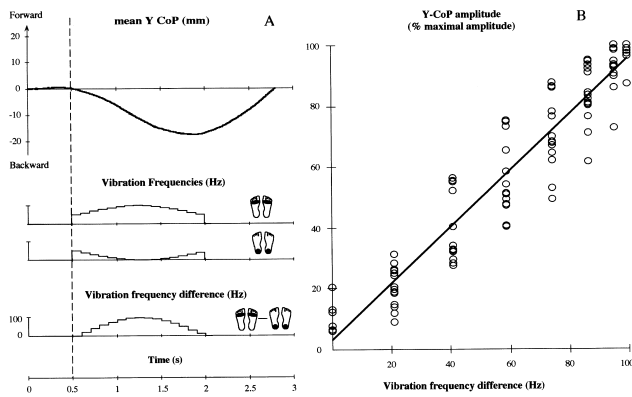


Fig. 3. Postural response induced under the 'dynamic contrast' condition: the forefoot and rear foot zones were co-stimulated at different frequencies following a sinusoidal pattern. (A) Mean Y-CoP displacement of all subjects synchronized on the CoP sway latency. (B) Correlation between the variations of the Y-CoP amplitude, expressed in percent of the maximal deviation, with the differences in vibration frequencies applied to the forefoot and rear foot zones. Note that the amplitudes of the Y-CoP sway varied linearly with the vibration frequency difference ($R^2 = 0.91$).

city of the postural responses were significantly higher at each frequency from 20 to 100 Hz. In addition, with as little as 20 Hz vibration, amplitude and velocity of the postural responses differed significantly from control (Fig. 1B).

On the contrary, simultaneous vibration of the four plantar zones at 20, 60 or 100 Hz never induced clearly oriented displacement of the body; only the postural instability slightly increased. Neither the mean amplitudes or velocities of the X- and Y-CoP sways changed with vibration frequency, and neither differed significantly from control ($P > 0.5$) (Table 1).

Postural responses induced under the 'static contrast' conditions: the 'static contrast' conditions resulted in postural responses consistent with the ones reported above. During the first second of co-stimulation (100 Hz) of the four plantar areas, the CoP oscillated slightly. When we suddenly stopped two of the four vibrators, an oriented whole-body tilt occurred. Its direction was always opposite to the cutaneous sites still stimulated, i.e. backward for the anterior zone stimulation and forward for the posterior zone stimulation (Fig. 2).

In addition, the forward body tilt induced under the 'static contrast' condition and the tilt after the rear foot zones were vibrated at 100 Hz did not differ significantly in their mean amplitude (52.1 ± 20.5 ; 42.9 ± 19 mm, Student's paired t -test: $P = 0.11$) and in velocity (26 ± 12.1 ; 27.1 ± 10.6 mm/s, $P = 0.71$). Likewise, the mean amplitudes (-34.3 ± 15 ; -36.2 ± 15.3 mm, $P = 0.76$) and velocities (-19.1 ± 10.4 ; -24.2 ± 12.5 mm/s, $P = 0.23$) of the backward body tilts induced by the 'static contrast' and by the forefoot zone stimulation at 100 Hz did not differ significantly.

Postural responses induced under the 'dynamic contrast'

condition: when the two anterior and the two posterior sole areas were co-stimulated with two sinusoidal patterns of vibration frequency in opposing phase, sinewave-like body sways were induced with a mean phase of $52 \pm 30^\circ$. The direction and amplitude of the mean Y-CoP displacement changed according to the difference between the frequencies applied to the forefoot and rear foot zones (Fig. 3A). The CoP was first backward-directed when the frequency was progressively increased from 50 to 100 Hz at the forefoot zones, and it correlatively decreased from 50 to 0 Hz at the rear foot zones. Then, when the frequency was decreased from 100 to 50 Hz at the forefoot zones and inversely increased from 0 to 50 Hz at the rear foot zones, the CoP was displaced forward.

In addition, we tested the hypothesis of a linear relation between the variations in amplitude of the Y-CoP displacement and the vibration frequency differences between the forefoot and rear foot zones. Since the vibration frequency varied every 100 ms during the 1.5 s of stimulation, the Y-CoP displacement of each subject was divided into 15 bins. For each bin, the mean Y-CoP amplitude expressed in percent of the maximal backward deviation was correlated with the corresponding value of the vibration frequency difference, using a linear regression model. For all the subjects, the Y-CoP variations increased linearly with the vibration frequency differences (Fig. 3B).

That selectively vibrating the anterior and posterior skin areas of the two soles induced whole-body tilts oriented in the direction opposite to the vibrated site whatever the frequency tested supports our previous data [5]. This phenomenon confirmed that tactile afferents from the main foot supporting areas contribute to stance control and that superficial low amplitude vibration is a particularly relevant stimulation to experimentally manipulate these tactile sensory inputs. Recordings of afferent fibers from the skin of the human foot dorsal part have demonstrated that, provided they were applied to their receptive fields, rapidly and slowly adapting cutaneous receptors responded proportionally to vibration-frequency between 1 and 200–300 Hz [8]. Moreover, slowly adapting receptors are known to precisely encode static pressures and changes in the pressure intensity [11]. That both the amplitude and the velocity of the postural responses increased with the vibration frequency whatever the plantar sites stimulated is consistent with these properties of cutaneous mechanoreceptors. Therefore, one can expect that, by coding the spatial origin and intensity of the pressure changes simulated by the vibration, the cutaneous mechanoreceptors of the soles inform the CNS that the body is tilted in the direction of the pressure increase and that a compensatory whole-body shift occurs in the opposite direction.

Of course, muscle spindle primary endings are also sensitive to mechanical vibration, but three arguments favor a mainly tactile origin of these postural effects upon vibrating the soles. First, that vibration would spread from the soles up to the intrinsic foot muscles or the leg muscles fails to

explain the direction of these postural responses. If such spread occurred, body shifts resulting from the activation of intrinsic foot muscle proprioceptors would always be oriented in the same direction whatever the plantar site stimulated and would reach a maximal amplitude after vibration of both feet. Second, in the case of two-heel vibration, a strong activation of leg muscle spindles would induce a backward body tilt, as when the Triceps surae are stimulated [9]. Third, submitting subjects to long lasting vibration of the soles (20 s) never evoked kinesthetic illusory sensations, whereas it does for ankle muscle vibration [5].

However, stimulating only the forefoot or the rear foot zones at 100 Hz or suddenly stopping the stimulation of one of them while the other one remained vibrated at 100 Hz resulted in postural responses with similar direction, amplitude, and velocity. This could mean that a pressure increase under one plantar zone or a pressure decrease under the opposite one is similarly interpreted by the CNS. Furthermore, co-stimulating these two plantar zones at different vibration frequencies induced body tilts whose direction always depended on where the higher frequency was applied, and whose amplitude varied according to the value of this frequency difference: when the vibration frequency applied to the forefoot areas was greater than that of the rear foot areas, the response was oriented backward, and conversely.

Taken together, these results strongly suggest that an artificial contrast between the pressures simulated on every anterior and posterior area of the soles can be a particularly efficient cue to indicate to the CNS how far the body has deviated from its vertical position. The postural reaction, adjusted in direction and amplitude, would seek to cancel the pressure difference, thus resetting the body stance. This suggestion is also supported by the fact that, whatever the frequency tested, no oriented body tilts were observed when the same frequency was applied simultaneously to the four zones of both soles. In this case, the tactile sensory messages probably indicate that the distribution of the plantar pressures was close to that of quiet stance; consequently, no compensatory response was needed.

That the CNS can deduce a spatial body position cue from the relative pressures distributed between the main supporting plantar areas can also explain that an erroneous perception of a lateral body tilt occurred after one sole of standing subjects was anesthetized [1]. Similarly, using supporting surfaces of different densities under the forefoot and rear foot zones, Lipshits [6] demonstrated that the reorganization

of the tonic EMG activities of the leg muscles depended on the pressure difference applied to these two zones. Also, the medium and long latency responses occurring in the ankle muscles after a rapid rotation of the supporting surface clearly correlated with the dynamic changes in the pressure differences between the anterior and posterior sole areas [12].

In conclusion, results show that the contribution of tactile afferents from the soles to human stance control can be precisely quantified but this contribution needs to be evaluated relative to that of other sensory channels.

- [1] André-Deshays, C. and Revel, M., Rôle sensoriel de la plante du pied dans la perception du mouvement et le contrôle postural. *Méd. Chir. Pied*, 4 (1988) 217–223.
- [2] Diener, H.C., Dichgans, B., Guschlbauer, B. and Mau, H., The significance of proprioception on postural stabilization as assessed by ischemia. *Brain Res.*, 296 (1984) 103–109.
- [3] Fitzpatrick, R., Rogers, D.K. and McCloskey, D.I., Stable human standing with lower-limb muscle afferents providing the only sensory input. *J. Physiol.*, 480 (1994) 395–403.
- [4] Horak, F.B., Nashner, L.M. and Diener, H.C., Postural strategies associated with somatosensory and vestibular loss. *Exp. Brain Res.*, 82 (1990) 167–177.
- [5] Kavounoudias, A., Roll, R. and Roll, J.P., The plantar sole is a 'dynamometric map' for human balance control. *NeuroReport*, 9 (1998) 3247–3252.
- [6] Lipshits, M.I., The influence of foot-support interactions on tonic activity in leg muscles during standing. *Fiziol. Cheloveka*, 19 (1993) 86–94.
- [7] Magnusson, M., Embon, H., Johansson, R. and Pyykkö, I., Significance of pressor input from the human feet in anterior-posterior postural control. *Acta Otolaryngol.*, 110 (1990) 182–188.
- [8] Ribot, E., Vedel, J.P. and Roll, J.P., Vibration sensitivity of slowly and rapidly adapting cutaneous mechanoreceptors in the human foot and leg. *Neurosci. Lett.*, 104 (1989) 130–135.
- [9] Roll, J.P. and Roll, R., From eye to foot: a proprioceptive chain involved in postural control. In B. Amblard, A. Berthoz and F. Clarac (Eds.), *Posture and Gait*, Elsevier, Amsterdam, 1988, p. 155.
- [10] Thoumie, P. and Do, M.C., Changes in motor activity and biomechanics during balance recovery following cutaneous and muscular deafferentation. *Exp. Brain Res.*, 110 (1996) 289–297.
- [11] Vedel, J.P. and Roll, J.P., Response to pressure and vibration of slowly adapting cutaneous mechanoreceptors in the human foot. *Neurosci. Lett.*, 34 (1982) 289–294.
- [12] Wu, Ge. and Chiang, J.H., The significance of somatosensory stimulations to the human foot in the control of postural reflexes. *Exp. Brain Res.*, 114 (1997) 163–169.